



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification: H04B	A2	(11) International Publication Number: WO 00/49721 (43) International Publication Date: 24 August 2000 (24.08.2000)
(21) International Application Number: PCT/US00/04286		Published
(22) International Filing Date: 18 February 2000 (18.02.2000)		
(30) Priority Data: 09/253,819 19 February 1999 (19.02.1999) US		
(60) Parent Application or Grant CORVIS CORPORATION [/]; (O. GRUBB, Stephen, G. [/]; (O. ZANONI, Raymond [/]; (O. STEPHENS, Thomas, D. [/]; (O. BOGGAVARAPU, Deepak [/]; (O. JIN, Ruxiang [/]; (O. ANTONE, Michael, C. ; (O.		

(54) Title: OPTICAL TRANSMISSION SYSTEMS INCLUDING SIGNAL VARYING DEVICES AND METHODS
(54) Titre: SYSTEMES DE TRANSMISSION OPTIQUES COMPRENANT DES DISPOSITIFS A VARIATION DE SIGNAL ET PROCEDES

(57) Abstract

Optical systems of the present invention include a plurality of optical processing nodes in optical communication via a plurality of signal varying devices. A first signal varying device includes an optical fiber configured to produce Raman scattering/gain in a signal wavelength range and a first signal variation profile. A first pump source is configured to provide sufficient pump energy in a plurality of first pump wavelengths to stimulate Raman scattering/gain in the optical fiber within the signal wavelength range. A second signal varying device is provided having a second signal variation profile to produce a cumulative signal variation profile that differs from the first and second signal variation profiles.

(57) Abrégé

Les systèmes optiques de la présente invention comprennent une pluralité de noeuds de traitement optiques dans une communication optique via une pluralité de dispositifs à variation de signal. Un premier dispositif à variation de signal comprend une fibre optique configurée de façon à produire un(e) gain/diffusion Raman dans une plage de longueur d'onde du signal et un premier profil de variation du signal. Une première source de pompage est configurée de façon à fournir une énergie de pompage suffisante dans une pluralité de premières longueurs d'ondes de pompage afin de stimuler un(e) gain/diffusion Raman dans la fibre optique, dans la plage de longueur d'onde du signal. Un second dispositif à variation de signal possède un second profil de variation de signal destiné à produire un profil de variation de signal de cumul différent des premier et second profils de variation de signal.

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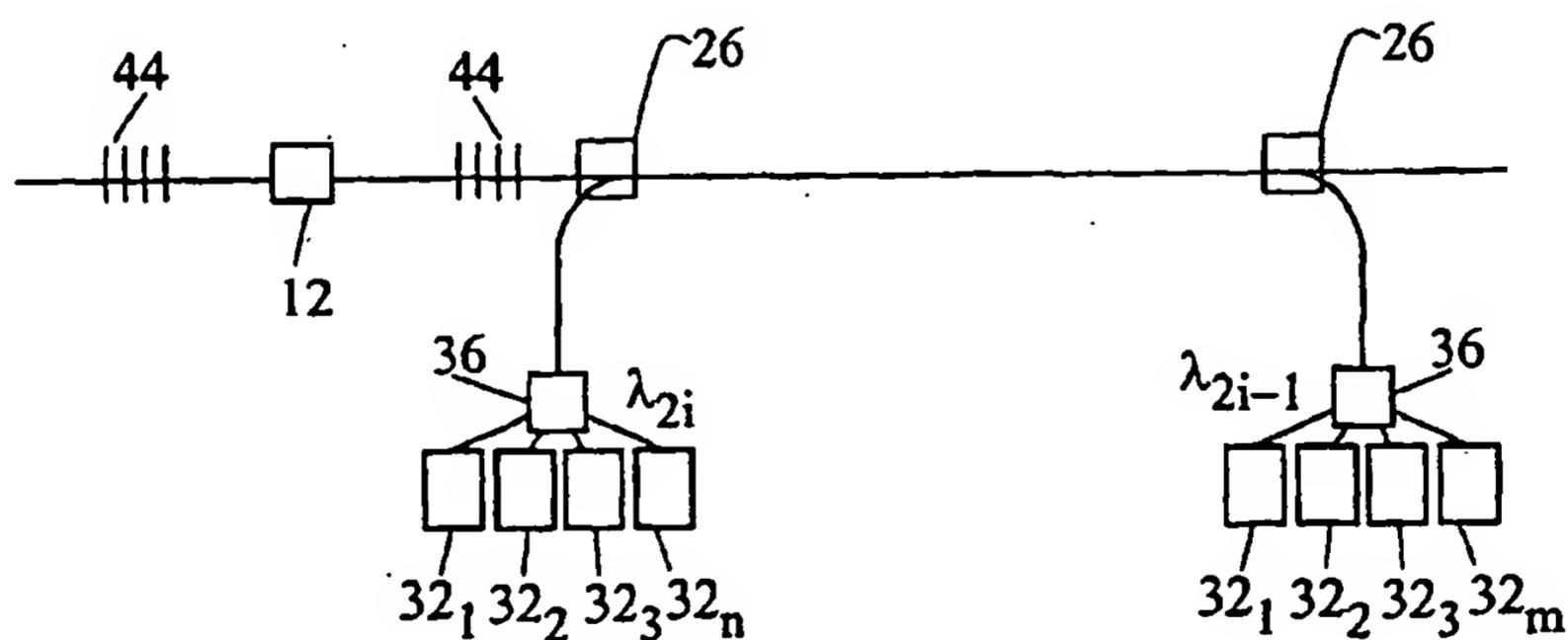
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H04B		(43) International Publication Date: 24 August 2000 (24.08.00)
(21) International Application Number: PCT/US00/04286		(81) Designated States: BR, CA, CN, JP, MX, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).
(22) International Filing Date: 18 February 2000 (18.02.00)		
(30) Priority Data: 09/253,819 19 February 1999 (19.02.99) US		Published <i>Without international search report and to be republished upon receipt of that report.</i>
(71) Applicant: CORVIS CORPORATION [US/US]; Intellectual Property Department, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US).		
(72) Inventors: GRUBB, Stephen, G.; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US). ZANONI, Raymond; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US). STEPHENS, Thomas, D.; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US). BOGGAVARAPU, Deepak; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US). JIN, Ruxiang; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US).		
(74) Agent: ANTONE, Michael, C.; Corvis Corporation, 7015 Albert Einstein Drive, Columbia, MD 21046-9400 (US).		

(54) Title: OPTICAL TRANSMISSION SYSTEMS INCLUDING SIGNAL VARYING DEVICES AND METHODS



(57) Abstract

Optical systems of the present invention include a plurality of optical processing nodes in optical communication via a plurality of signal varying devices. A first signal varying device includes an optical fiber configured to produce Raman scattering/gain in a signal wavelength range and a first signal variation profile. A first pump source is configured to provide sufficient pump energy in a plurality of first pump wavelengths to stimulate Raman scattering/gain in the optical fiber within the signal wavelength range. A second signal varying device is provided having a second signal variation profile to produce a cumulative signal variation profile that differs from the first and second signal variation profiles.

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Description

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OPTICAL TRANSMISSION SYSTEMS INCLUDING SIGNAL VARYING
DEVICES AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation in part of commonly
10 assigned U.S. Serial No. 09/119,556 filed July 21, 1998
entitled "Optical Signal Varying Devices", which is
incorporated herein by reference.

15

FIELD OF THE INVENTION

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The present invention is directed generally to optical
10 signal varying devices that provide for controllably
varying optical signal characteristics. More particularly,
20 the invention relates to optical transmission including
optical amplifiers and attenuators that have controllable
gain, loss and transparent intensity variation profiles for
15 use in optical communication systems.

25

BACKGROUND OF THE INVENTION

30

The continued development of digital technology has
provided electronic access to vast amounts of information.
The increased access to information has fueled an
30 increasing desire to quickly obtain and process the
information. This desire has, in turn, driven demand for
faster and higher capacity electronic information
processing equipment (computers) and transmission networks
35 and systems linking the processing equipment (telephone
lines, cable television (CATV) systems, local, wide and
metropolitan area networks (LAN, WAN, and MAN)).

40

In response to this demand, telecommunications
companies have turned to optical communication systems to
provide substantially larger information bandwidth
30 transmission capacities than traditional electrical
communication systems. Early optical transmission systems,
known as space division multiplex (SDM) systems,
transmitted one information signal using a single
wavelength in separate waveguides, i.e. fiber optic strand.
35 Time division multiplexing (TDM) multiple information
signals onto a single wavelength in a known sequence that

50

5 can be separated upon receipt has further increased the transmission capacity of optical systems.

10 The continued growth in traditional communications systems and the emergence of the Internet as a means for 15 accessing data has further accelerated the demand for higher capacity communications networks.

15 Telecommunications companies have looked to wavelength division multiplexing (WDM) to further increase the capacity of their existing systems.

20 10 In WDM transmission systems, pluralities of distinct TDM or SDM information signals are carried using 25 electromagnetic waves having different wavelengths in the optical spectrum, i.e., far-UV to far-infrared. The pluralities of information carrying wavelengths are 30 combined into a multiple wavelength optical signal, which is transmitted in a single waveguide. In this manner, WDM systems can increase the transmission capacity of existing 35 SDM/TDM systems by a factor equal to the number of wavelengths used in the WDM system.

40 20 Optical WDM systems were not initially deployed, in part, because of the high cost of electrical signal 45 regeneration/amplification equipment required to compensate for signal attenuation for each optical wavelength throughout the system. However, the development of the 50 25 erbium doped fiber optical amplifier (EDFA) eliminated the need for, and the associated costs of, electrical signal regeneration/amplification equipment to compensate for signal attenuation in many systems. Thus, WDM systems became a cost effective means to increase optical network 30 capacity.

55 45 Erbium doped fiber amplifiers ("EDFAs") can 50 theoretically be used to amplify signals in an amplification wavelength range spanning from approximately 1500 nm and 1600 nm. However, EDFAs do not equally amplify 35 each optical signal wavelength within the range. The differences in amplification can result in attenuation of some signals and/or signal loss or distortion because of highly amplified noise. Thus, the performance of EDFAs in

5 a transmission system varies depending upon the number of wavelengths and the wavelengths used in the system.

10 Judicious selection of the wavelengths and amplifier powers used in a system can minimize EDFA variations (gain 5 non-uniformities). For example, many WDM systems currently restrict the wavelengths used in the system to between 1540 nm and 1560 nm, a range in which EDFAs comparably amplify 15 optical signals. As might be expected, restricting system designs to only those wavelengths that are comparably 10 amplified by EDFAs severely limits the number of wavelengths and the information transmission capacity of WDM systems.

20 The number of wavelengths in the system can be increased to some extent, if only a small number of 15 amplifiers are used in the system. A broader range of wavelengths can be used with a less stringent requirement 25 for uniform amplification, because cumulative amplifier variations will generally not swamp out lowly amplified signals over a small number of amplifiers.

30 20 In addition to the wavelength dependence, EDFA performance is also a function of the amplification power supplied to the EDFA. Thus, EDFAs generally must be 35 operated with a limited power range to minimize 25 amplification variations in the system. The amplifier power limitations, in turn, increase the number of amplifiers in a system by limiting the allowable distance 35 between EDFAs, i.e., the span length.

40 In discussing the signal intensity variation of EDFAs and other devices, the uniformity of gain or loss profiles 30 over a wavelength range is generally referred to as the 45 flatness of the profile. A perfectly flat profile is a gain, loss, or transparency profile that has a constant value over the wavelength range of interest.

45 WDM system constraints imposed by EDFA wavelength 35 variations have focused attention on providing EDFA 50 configurations that compensate for the variations and provide more uniform gain for a larger band of wavelengths and over a greater power range. Various EDFA

5 configurations have been proposed to minimize amplifier
gain variations. For example, see U.S. Patent Nos.
5,406,766, 5,541,766, 5,557,442, 5,636,301, and 5,696,615;
10 Sugaya et al., Optical Amplifiers and Their Applications,
5 Technical Digest OSA 1995 v. 18, pp. 158-161/FC3-1;
Jacobovitz-Veselka et al., Optical Amplifiers and Their
Applications, Technical Digest OSA 1995 v. 18, pp. 162-
165/FC3-1;; Park et al., Electronics Letters, March 5,
15 1998, Vol. 34, No. 5, Online No. 19980346; and, Dung et
10 al., Electronics Letters, 19 March 1998, v. 34, n. 6,
Online No. 19980446.

20 Other amplifier configurations have used EDFA's in
combination with a Raman amplifier to statically vary the
gain profile of an EDFA. For example, see Masuda et al.,
25 OSA 1997, pp. 40-3/MC3-1, Masuda et al., Electronics
Letters, v34, n13, Online No. 19980935 (June 25, 1998), and
U.S. Patent No. 5,083,874 issued to Aida et al. It has
also been proposed to eliminate EDFA's and use amplifier
30 configurations that employ only Raman amplifiers. However,
the all-Raman configurations to date have not greatly
improved the amplifiers gain flatness profile and may still
require gain equalization to flatten the gain profile as
discussed by Rottwitt et al., "A 92 nm Bandwidth Raman
35 Amplifier", OFC '98, p. 72/CAT-1.

40 The above referenced gain flattened configurations are
generally statically configured to have a wavelength range
45 defined by a 3 dB variation (- a factor of 2) in the gain
profile and having a ± 1 dB variation between wavelengths.
The gain flattened amplifiers provide some improvement over
conventional EDFA's in the number of amplifiers, amplifier
50 power ranges, and span lengths before the signal must be
regenerated. The gain flattened optical amplifiers
nonetheless introduce excess amplifier noise and gain
nonuniformities that limit the number of optical amplifiers
that can be used in a WDM system prior to signal
regeneration.

55 Gain flattening in optical amplifier configurations is
generally performed using filters and/or attenuators to

5 decrease the signal intensity of the wavelengths to a
specified value. For example, in many embodiments, the
optical signals are amplified to an intensity higher than
the amplifier output value and the filters and attenuators
10 5 are used to flatten the gain profile by decreasing the
optical signal intensity. These methods tend to increase
the noise in the signal with a corresponding decrease in
the output power of the device.

15 Optical filters and attenuators are often included as
10 15 separate optical devices in the system, but may also be
all-fiber devices, such as Bragg grating filters and all-
fiber attenuators, included in the transmission fiber. For
example, see U.S. Patent Nos. 4,728,170, 5,095,519,
20 25 5,633,974, 5,651,085, and 5,694,512. The filters and
attenuators can be variable or fixed depending upon the
configuration. The amplifier, filters, and attenuators are
statically configured to flatten the gain profile.

25 As the demand for transmission capacity continues to
grow, there is an increasing need for systems that span
30 35 longer distances and provide a greater number of
information carrying wavelengths/channels. However, it has
proven difficult to balance the non-linear gain of EDFA
configurations with selective wavelength filtering and
attenuation to provide gain flattened amplifier
40 45 configurations that meet this need.

35 Accordingly, there is a need for optical amplifiers
and attenuator particularly, and signal varying devices
generally, that provide increased control over the spectral
intensity profile of optical signal in the optical systems.
40 45 The improved signal varying devices will provide for higher
capacity, more versatile, longer distance communication
systems.

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5 BRIEF SUMMARY OF THE INVENTION

The apparatuses and methods of the present invention address the above difficulties with prior art optical devices and systems. An optical system of the present 10 invention includes a plurality of optical processing nodes in optical communication via at least one signal varying device. The signal varying devices includes an optical fiber suitable for facilitating Raman scattering/gain in a signal wavelength range and a pump energy source for 15 providing pump energy in a plurality of pump wavelengths. The pump source provides sufficient pump energy in each pump wavelength to stimulate Raman scattering/gain in the 20 optical fiber within the signal wavelength range.

The signal varying device can be embodied as a 15 distributed device that employs a portion or all of an optical transmission fiber extending between two optical 25 nodes, such as between an optical transmitter and an optical receiver. The signal varying device can also be embodied as a lumped or concentrated device that is placed 20 in the optical transmission fiber at discrete locations between the optical nodes.

The pump wavelengths are selected such that the 30 combined Raman gain resulting from the pump energy supplied by each pump wavelength produces a desired signal variation 35 profile in the signal wavelength range. In addition, the pump energy supplied by at least one of the pump wavelengths can be dynamically varied to produce a controlled signal intensity variation profile over the 40 signal wavelength range in the optical fiber. In an embodiment, four pump wavelengths spaced in 10-30 nm 30 intervals can be used to provide intensity gain and flatness control to over 30 nm to within ± 0.2 dB.

45 Also in an embodiment, erbium doped fiber is included in the signal varying device to provide a multiple stage 35 signal varying device. The erbium doped fiber and the multiple wavelength controlled Raman portion of the signal

5 varying device can be operated in conjunction to impart a
desired intensity profile to the optical signal.

10 The design and length of the optical fiber used in
conjunction with the pump source can be tailored to provide
15 5 flexibility in operation of the system. For example, a
concentrated, or lumped, high gain signal varying device
can be provided using a small core fiber, such as
dispersion compensated or dispersion shifted fiber. The
lumped device further provides for a greater range over
15 10 which the signal varying device can be used as an
attenuator because of its higher localized loss.

20 Multistage concentrated and/or distributed Raman
signal varying devices can also be employed to further
tailor the profile using either separate or common pump
25 15 sources. For example, a first concentrated Raman stage can
employ small core fiber to provide for efficient Raman
amplification of the signal wavelengths. A second
concentrated Raman stage can employ a larger core fiber to
further amplify the signal power, while lessening the
25 20 extent of non-linear interactions amongst the signal
wavelengths that may occur in a single stage with smaller
30 core fibers. The second concentrated Raman stage can also
employ fiber having low loss in the 1400-1520 nm range to
allow for more efficient Raman pumping of the multiple
35 25 stages using a common source. In addition, the first and
second Raman stages can use fibers that have different
chromatic dispersion characteristics to further reduce the
extent of non-linear interaction between the signal
wavelengths.

40 30 Distributed signal varying devices can be provided by
employing the optical transmission fiber spanning between
the optical nodes to control the signal variation profile
occurring in the transmission fiber. Also, different
45 35 optical fiber types, including doped fibers, can be used in
various portions to replace existing transmission fiber to
provide for different distributed signal varying profiles.
The concentrated and distributed Raman signal varying
50 devices can be used alone or in combination to statically

5 or dynamically impart desired signal varying profile
characteristics to the system.

10 In an embodiment, a distributed Raman amplifier can be
employed with one or more first pump sources propagating
15 pump energy in the transmission fiber to amplify counter-
propagating signal wavelengths to provide a first signal
varying profile. A concentrated Raman signal varying
device can be placed in series with the distributed Raman
amplifier employing one or more second pump sources to
15 provide a second signal varying profile. The first and
second signal varying profiles acting to produce a desired
overall signal varying profile. Additionally, an EDFA can
be employed to contribute a third signal varying profile to
the overall signal varying profile.

20 15 A distributed Raman amplifier can also be used to
provide pump energy to one or more remotely located
25 concentrated or distributed Raman amplifiers and/or doped
amplifying fibers. For example, the pump sources can be
selected to produce a first signal varying profile in the
20 distributed Raman amplifier and a second signal varying
profile in the remotely located erbium doped fiber. The
30 pump power and/or the wavelength of the pump energy sources
can be varied to control to individual and overall signal
varying profiles. Pump energy can also be supplied to
35 25 remotely located signal varying devices using one or more
separate fibers. Such fibers can be pure SiO₂ to minimize
loss and nonlinear conversion of the pump light.

40 Additional gain and gain profile control in Raman
amplifier stages can be produced by including one or more
30 pumps at lower Raman wavelengths that serve to provide
additional pump energy to the higher Raman pump
wavelengths. The pump source can employ numerous
45 configurations to decrease the extent of interference,
i.e., cross-talk, that occurs between the Raman pump
35 wavelengths, as well as the signal wavelength.

50 Thus, the devices and methods of the present invention
provide for control of the signal intensity over a range of
wavelengths in optical transmission systems. Accordingly,

5 the present invention addresses the aforementioned problems
and provides signal varying devices, methods, and optical
systems that provide increased control over optical signal
characteristics in the system. These advantages and others
10 5 will become apparent from the following detailed
description.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Embodiments of the present invention will now be
described, by way of example only, with reference to the
10 accompanying Figures wherein like members bear like
reference numerals and wherein:

20 Figs. 1-2 shows optical communication systems of the
present invention;

15 Figs. 3-5 show signal varying devices of the present
invention;

25 Figs. 6-7 show remote pumping embodiments of the
present invention;

30 Fig. 8 shows exemplary overall, distributed Raman, and
remote erbium gain profiles using remote pumping
20 embodiments of the present invention;

35 Figs. 9-10 show alternative pump combining
configurations of the present invention;

40 Figs. 11(a&b) show (a) Raman gain profiles over a 30
nm range as a function of gain and (b) various Raman gain
35 profiles; and,

45 Figs. 12-13 show Raman gain profiles over 35 and 100
nm, respectively, based on a summation of experimental data
using single pump wavelength signal varying devices.

DETAILED DESCRIPTION OF THE INVENTION

30 The optical systems 10 of the present invention will
be described generally with reference to the drawings for
45 the purpose of illustrating present embodiments only and
not for purposes of limiting the same.

35 Fig. 1 shows an optical system 10 including a signal
50 varying device 12 optically connecting two optical
processing nodes 14 to form an optical link 15. As shown

5 in Fig. 2, the optical processing nodes 14 generally include at least one transmitter 16 for transmitting optical signals in at least one information carrying wavelength, or channel, or at least one optical signal
10 5 receiver 18 for receiving the optical signals.

As is known in the art, the transmitter 16 includes at least one optical source or emitter, such as lasers, incoherent sources, or other sources to provide one or more optical carriers at fixed or tunable wavelengths. The
15 10 information to be transmitted in the system 10 can be used to directly modulate the source or externally modulate the optical carrier, or can be upconverted onto an optical wavelength other than the optical carrier wavelength.
20

Likewise, the receiver 18 can employ direct or
15 25 indirect, e.g. coherent, detection equipment, such as photodiodes and wavelength selective devices as are known in the art, to receive and perform an opto-electronic conversion of the signal. Similarly, the optical receiver 18 can detect a fixed or tunable wavelength depending upon
30 20 the requirements of the system 10. The optical processing nodes 14 may further include add and/or drop ports 20, switches 22, signal distributors 24 and combiners 26, or other signal processing devices as are further known in the art.

35 25 The optical system 10 may include a plurality of optical links 15 interconnected via the optical processing nodes 14 and/or signal varying devices 12. The optical processing nodes 14 can serve as terminals in the optical system 10 or may be disposed intermediately along optical
40 30 transmission fiber 28 interconnecting the nodes 14 and devices 12.

45 35 As shown in Fig. 2, the signal varying device 12 includes a Raman gain section of transmission fiber 30 in optical communication with the processing nodes 14, which is supplied with pump energy by a pump energy source 32. The signal varying device 12 can be embodied as a distributed device in which the Raman gain transmission
50 50 fiber 30 includes a substantial portion or all of the

5 optical transmission fiber 28 extending between nodes 14, such as a optical transmitter 16 and optical receiver 18, and/or devices 12. The signal varying device 12 can also be embodied as a lumped, or concentrated, device that is
10 5 placed in the optical transmission fiber 28 at discrete locations between the optical nodes 14.

15 One skilled in the art will appreciate that concentrated devices 12 of the present invention can be produced in a manner analogous to prior art EDFA 10 construction. For example, the concentrated devices 12 are constructed by winding optical fiber of sufficient length to provide the desired signal variation range, such as 20 amplification, within a discrete device around a spool to control the size of the devices 12.

15 As shown in Fig. 3, a controller 34 can be included in
20 the device 12 and configured to dynamically control the
25 pump energy supplied via one or more of the pump
30 wavelengths. Dynamic control of the pump energy allows for
35 the performance of the device 12 to be varied as signal
40 transmission changes occur, either upstream and/or
45 downstream of the device 12. Thus, the dynamic control
50 provides the ability to continually or periodically modify
55 the operation of the devices 12 in response to
60 communication system/environmental variations that
65 inevitably occur with time. The devices 12 allow the
70 signal varying profiles to be controlled both on-line or
75 off-line, such as during installation, maintenance,
80 grooming, etc.

40 In one aspect of the invention, the pump source 32 is
30 configured to combine arbitrarily spaced pump wavelengths
as shown in Fig. 3. Grating stabilized lasers 32_m can be
used to provide pump wavelengths that are combined in pairs
using fused DWDM couplers 36. The paired pump wavelengths
45 can be further combined with arbitrarily spaced pump
wavelengths using a dichroic filter 38. Alternatively,
35 polarization combiners 39 can be used to combine two pump
wavelengths having orthogonal polarizations, which can be
50 further combined with other wavelengths using the dichroic

5 filter 38. The use of polarization combiners 39 provides additional control over the pump energy polarization and the resulting pump energy conversion in the Raman amplifiers.

10 5 The combination of fused couplers 36, dichroic filter 38, and polarization combiners 39 in the present invention provides increased flexibility in wavelength combining and amplifier gain profile control. It will be appreciated that 15 additional wavelengths can be added by cascading the lasers and wavelength combining arrangements.

10 15 The pump energy is introduced into the optical transmission fiber 28 using combiners 26, such as wavelength division multiplexers. Other wavelength selective or non-selective couplers, circulator, reflectors, and other combining device known in the art can be used to introduce the pump energy.

20 25 In the present invention, the Raman gain optical fiber 30 can be selected to facilitate Raman scattering/gain over a range of transmission signal wavelengths that include 20 30 optical signal wavelengths $\lambda_{s1}-\lambda_{sn}$, when the fiber 30 is stimulated using pump energy provided in a pump wavelength range. Most silica-based fiber, including most 35 transmission fibers, facilitate Raman gain in a wide range of wavelengths; thus, additional fiber 30 included in the 40 device 12 is generally selected to complement any existing fiber as will be further discussed. With proper pump wavelength selection, it is expected that Raman gain can be provided across the optical fiber transparent transmission wavelength range, which currently ranges from approximately 30 45 50 1240 to 1650 nm for silica based fiber.

45 55 For example, in the transmission signal wavelength range of 1520 nm to 1620 nm, the corresponding pump wavelength range is approximately 1420 nm to 1520 nm. Likewise, in the transmission signal wavelength range of 35 50 1250 nm to 1350 nm, the corresponding pump wavelength range is 1150 nm to 1250 nm. Thus, more than one signal wavelength range can be transmitted in the optical system 10. The signal wavelength ranges can be interleaved with

5 the pump wavelengths to provide a multiple signal wavelength range system as stated above. It is also expected that changes in the optical fiber transmission signal wavelength range can be accommodated by the present
10 5 invention by proper selection of pump wavelengths.

Devices 12 having different signal variation profiles and employing different pump wavelengths can be used in combination within the system 10. The optical fiber 30 used in the signal varying device 12 can be the same as the
15 10 transmission fiber 28 in the system 10 or another type of optical fiber having different properties. The length and type of fiber deployed in the system 10 can be tailored to provide flexibility in the operation of the system.
20

For example, the extent of Raman scattering in the
15 15 fiber is partly dependent upon the size of the optical fiber core. In addition, the loss in the fiber increases as the size of the core decreases. Thus, a concentrated, or lumped, high gain/loss signal varying device can be provided using a small core fiber. Also, some fiber core
25 20 composition, such as cores with increased germania concentrations, can provide for wider Raman gain variation profiles. In addition, fibers can be chosen to impart other characteristics, i.e., chromatic dispersion, to the
30 30 optical signals that may differ from those of the
35 35 transmission fiber.

In at least one embodiment, a small core dispersion compensating fiber ("DCF"), such as is manufactured by Lucent Technologies or Sumitomo Electric Company, is used as the Raman gain fiber in a concentrated signal varying
40 30 device 12. The DCF concentrated device 12 provides for a greater range over which the signal varying device can be used as an attenuator, an amplifier, or a transparent link, because of the high attenuation/high gain properties of the
45 35 DCF. Conversely, standard single mode transmission fiber can be used to provide a distributed lower gain signal varying device 12 to provide control over a smaller intensity variation (gain/loss) range.
50

5 Non-linear intensity profiles can be also provided
using the device 12. The device 12 can include inherently
nonlinear or nonlinearly operated components, such as one
or more doped fiber amplifiers, etc., to produce a net
10 5 linear intensity profiles or different non-linear profiles.
For example, an erbium doped fiber 40 can be included in
the transmission fiber and optically pumped using
15 10 wavelengths, $\lambda_{p1} - \lambda_{pe1}$, supplied by one or more erbium pump
sources 42i. The erbium doped fiber 40 can be embodied as a
distributed or concentrated portion in combination with the
15 10 Raman section of the signal varying device to provide a
multiple stage signal varying device 12, as shown in Figs.
20 4 and 5. It will be appreciated that various EDFA
configurations, such as those discussed in the Background,
15 15 can be used in embodiments incorporating erbium doped
fiber.

25 Devices 12 having multiple concentrated/lumped Raman
stages can be introduced into the transmission fiber 28 to
further tailor the signal varying profile. For example, a
20 20 first concentrated Raman fiber stage 12₁ can employ a small
core fiber, such as DCF, to provide for efficient Raman
30 30 amplification of the signal wavelengths. A second
concentrated Raman fiber stage 12₂ can employ a larger core
fiber to provide additional signal amplification, while
35 35 lessening the extent of non-linear interactions compared to
smaller core fibers. The second concentrated Raman stage
can also employ fiber having low loss in the 1420-1510 nm
range, such as AllWave fiber sold by Lucent Technologies.
40 40 The use of low loss fiber provides increased pumping
efficiency, so that both stages can be more effectively
30 30 pumped using a common Raman pump source. Alternatively,
the pump source 32 can be configured to provide different
45 45 Raman pump wavelengths to pump the first and second stages.

45 In addition, the first and second Raman stages can use
35 35 fibers that have different chromatic dispersion
characteristics. The change in fiber dispersion
characteristics will tend to reduce the extent of non-

50

5 linear interaction that occurs between the highly amplified
signal wavelengths.

10 Other optical components including gain profile
varying components can be included in the devices 12. As
15 shown in Fig. 5(b), wavelength selective reflectors 44,
such as Bragg gratings, can be included to reflect excess
pump energy back into optical fiber 30 or erbium sections
40. Gain flattening filters 46 can also be included to
impart a fixed or variable gain profile on the optical
10 signal. Optical isolators 48 are provided to eliminate
discrete reflections from the gain flattening filter 46.
Also, the device 12 can be provisioned to allow the local
20 controller 34 to transmit and receive supervisory and/or
monitoring, i.e., service, information from a network
25 manager 50 via optical wavelength λ_{sc} as shown in Fig. 5(b).

30 Also, it will be further appreciated that the devices
35 12 can be divided into multiple stages, i.e., pre- and
post-amplifier stages. Signal processing, such as
40 adding/dropping or switching channels, etc., and/or
45 controlling accumulated noise and/or gain profile
variations can be performed between the stages as is known
50 in the art.

55 The pump energy source 32 provides pump energy to the
fiber 30 in a plurality of pump wavelengths, $\lambda_{p1}-\lambda_{pn}$, within
60 the pump wavelength range. The pump energy can be supplied
65 to the fiber 30 counter-directionally and/or
70 codirectionally with the optical signal wavelengths $\lambda_{s1}-\lambda_{sn}$
75 being transmitted in the system 10. Counter-propagating
80 the first Stokes order Raman wavelengths relative to the
85 signal wavelengths generally lessens signal degradation due
90 to interference, i.e., cross-talk, between the pump energy
95 and the optical signal. Also, the pump energy supplied via
each pump wavelength can be controlled to compensate for
any self-pumping that might occur between the pump
100 wavelengths. It is also desirable to select pump
wavelengths so that the pump energy supplied by each pump

50

5 wavelength is relatively uniform, i.e., within $\pm 10\%$ of the
average pump energy per pump wavelength.

10 In addition, the pump source 32 can supply the pump
energy at one or more points along the fiber 30 as shown in
15 Fig. 5(a). In at least one embodiment, pump energy is
separately supplied to each stage of the device 12 from a
point on the fiber 30 and counter-directionally to the
optical signals being transmitted.

15 The pump source 32 can be any source of pump energy
20 that is sufficient to induce Raman gain in the transmission
wavelength ranges of the system 10. Typically, the pump
source 32 will include one or more pump lasers of the type
known in the art, and may also include other coherent and
25 incoherent broad and narrow band sources. The number of
lasers and other pump energy sources used in the pump
source 32 depends upon the transmission wavelength ranges
over which the signal varying device 12 will be operated.

30 The pump wavelengths used in erbium fiber stages of
the devices 12 can be selected to provide pump energy in
35 the 980 nm range for only erbium gain or in the 1480 nm
range for both Raman and erbium gain. One will appreciate
that pump wavelengths in the 980 nm range may be used to
provide Raman gain by pumping successive Stokes orders in
the device 12, as discussed within.

40 The pump sources 32 may be locally or remotely located
35 from the signal varying device, such as shown in Figs 6 and
7. The signal varying devices 12 can be configured such
that the residual pump energy from a distributed Raman
amplifier is supplied to pump one or more concentrated or
45 distributed Raman and/or doped fiber signal varying devices
12. For example, sections of the transmission fiber are
replaced with corresponding sections of doped fiber and/or
different types fiber to provide distributed signal varying
50 devices 12. In these configurations, residual pump energy
from the distributed Raman amplifier can be used to pump
and control the signal variation profiles of the remotely
distributed devices 12.

5 Fig. 8 shows a plot of the signal variation profiles
10 using the transmission fiber 28 to form a distributed Raman
15 amplifier, which provides pump energy to a remotely located
20 section of erbium fiber 40 spliced into the transmission
25 fiber 28. Curve A shows the remote erbium gain profile.
30 Curves B and C show the target and achieved Raman gain
35 profile. Curve D shows the overall gain profile for the
40 erbium and the Raman gain section. As can be seen, the
45 pump wavelengths and energy provided by the pump source
50 can be selected to provide complementary non-linear gain
55 profiles in the transmission fiber 28 and the erbium fiber
60 40. The resulting overall profile is substantially
65 uniform. As would be expected the overall profile can be
70 varied to provide other profiles as may be desired. For
75 example, the gain profile can be tilted to offset higher
80 bending losses at longer wavelengths.

25 As shown in Fig. 6, a portion of the optical signal,
including the signal wavelengths, can be tapped off the
transmission fiber 28 for analysis. Characteristics of the
20 signal wavelengths can be determined using an analyzer 43,
such as an optical spectrum analyzer and a tunable receiver
30 18 and bit error rate test device. The signal
characteristics can be used by the controller 34 to vary pump
energy supplied by pump sources 32₁ - 32_m to maintain a
25 desired profile/system performance. The variation in pump
energy will change the overall signal varying profile by
35 varying profiles of both the remote signal varying device
12 and the distributed Raman amplifier supplying the remote
devices 12.

40 30 In addition, one or more wavelength selective
reflectors 44 can be disposed proximate to the remote
signal varying device 12. Thus, excess pump energy can be
reflected to provide additional gain in the distributed
45 Raman section and/or the remote signal varying devices
35 depending upon the position of the reflectors 44.

As further shown in Fig. 7, additional gain and gain profile control in Raman amplifier stages and remotely pumped doped fiber stages can be produced by including one

5 or more pumps at higher Stokes order Raman wavelengths to
10 amplify lower Stokes order Raman pump wavelengths. In
15 Raman amplifiers, the pump energy attenuates with distance
traveled in the fiber reaching a level at which very little
20 Raman amplification of the signal wavelengths occurs.
25 However, pump energy at higher Stokes order Raman
30 wavelengths (1320-1420 nm, etc.) can be introduced into the
35 fiber to amplify the lower Stokes order Raman wavelengths
(1420-1520 nm, etc.), which, in turn, will amplify the
40 signal wavelengths (1520-1620 nm, etc.). If co-propagating
45 Raman wavelengths are staggered by at least every other
50 Raman wavelength and adjacent Stokes orders are counter-
propagated, cross-talk between the wavelengths should not
greatly affect the signal wavelength.
55 An exemplary Raman wavelength pump arrangement is
shown in Fig. 7. Pump lasers 32_n supply Raman wavelengths
in the Stokes orders (2i-1) counter-propagating to the
60 signal wavelength range and Raman wavelengths in the Stokes
65 orders 2i co-propagating with the signal wavelengths for
70 values of i from 1 to an arbitrary value. For a signal
75 wavelength in the 1520 to 1620 nm range, the first and
80 second Raman wavelength ranges would be 1420-1520 nm and
85 1320-1420nm, respectively, which corresponds to i=1.
90 In some embodiments, information can be transmitted on
95 a wavelength in one direction, while providing pump energy
in the same wavelength in the other direction. For
100 example, in newer fibers that have lower loss in the 1400
105 nm range, information could be transmitted in one direction
110 at 1450 nm and pump energy supplied for Raman gain in the
115 1550 range in the other direction. When allocating the
120 same wavelength for use in both directions, consideration
125 must be given to potential signal degradation due to
130 Rayleigh back-scattering.
135 The pump wavelengths in the various Stokes' orders are
140 selected such that the combined Raman gain resulting from
145 the pump energy supplied by each pump wavelength produces a
150 desired Raman gain signal variation profile in the signal
155 transmission wavelength ranges. The Raman gain signal

5 variation profile can be uniform or nonuniform, linear or
nonlinear depending upon a particular application of the
device 12. In wide band optical systems, i.e., signal
wavelength range > 30 nm, the signal varying profile of the
10 5 devices 12 can be used to compensate for loss variation of
the signal wavelengths, such as bending loss variations,
etc.

15 The number of pump wavelengths and the wavelength
spacing used in the device 12 can be varied to provide
10 10 Raman gain over a range of wavelengths. The pump
wavelengths, $\lambda_{p1}-\lambda_{pm}$, are generally selected to provide
sufficient overlap of the Raman gain profiles to provide
20 20 control over the Raman gain at one or more wavelengths in
the transmission signal wavelength range.

25 15 In addition, the pump energy supplied by at least one
of the pump wavelengths can be controllably varied to
change the signal variation profile over the wavelength
range in the optical fiber. Also, the total pump energy
supplied via all the pump wavelengths can be held constant
30 20 or varied accordingly, while varying the pump energy
provided by the individual pump wavelengths. One skilled
in the art will appreciate that the choice of wavelength
can be made to tailor the signal varying characteristics of
the device 12 to a particular system configuration.

35 25 Typically, the pump wavelengths, $\lambda_{p1} - \lambda_{pm}$, are selected
so that overall signal variation profile will be
substantially uniform over the range of wavelengths. One
skilled in the art will appreciate that decreasing the
40 30 spacing intervals of the pump wavelengths can provide
increased control over the uniformity of the intensity
profile. For example, pump energy could be supplied in
narrow spectral ranges to maximize the gain in the signal
wavelengths will minimizing the gain of the noise
45 35 wavelength between the signals. However, the increased
uniformity and control must be balanced with the increased
cost of using additional wavelengths in the device 12 and
allowable total power requirements. Conversely, a
50

5 broadband optical source can be employed to provide pump energy over a broad spectral range of wavelengths, thereby minimizing the required number of pumps.

10 When a plurality of pump wavelengths are used, it is 5 generally necessary to employ cascaded combining arrangement. As the number of cascaded combining arrangements is increased or the range of wavelengths is varied, it may become necessary to employ other 15 arrangements to reduce the loss associated with combining 10 the pump energy. Such alternatives can include prism 52 and lens 54 combiners or circulator 56/grating 44 20 multiplexers, such as shown in Figs. 9 and 10. Figs. 9(a&b) show the use of a single prism 52 to combine a plurality of pump wavelengths. The plurality of pump 25 wavelengths are focused using either one or more lenses 54 at appropriate angles into the prism 52, which combines the plurality of pump wavelengths into a single beam that is output into optical fiber 30 in the device 12 or the transmission fiber 28. The difference in the angles of 30 incidence is determined based on the refractive indices of the prism for each wavelength.

35 The difference in the refractive indices for each wavelength can be used to calculate the angle of incidence on the prism for each wavelength. The index of refraction 25 in the prism is calculated as:

$$n(\lambda) = (A + B\lambda^2/(\lambda^2 - C) + D\lambda^2/(\lambda^2 - E))^{1/2} \text{ and}$$

$$\theta(\lambda) \text{ (radians)} = \arcsin(n(\lambda) * \sin(\alpha)),$$

40 where $\alpha = 22\pi/180$, θ is the refraction angle, λ is 35 the pump wavelength, and A-E are prism constants.

45 For example, a AgGaSe₂ prism (A-E= 3.9362, 2.9113, 0.1507, 1.7954, 1600) can be used to combine two pump 50 wavelengths at 1480 and 1470, respectively. The pump wavelengths are transmitted into the prism at angles which differ by approximately 0.136 degrees to produce a combined signal exiting the prism 52. One skilled in the art will appreciate that combining prisms 52 may also be cascaded

5 similar to couplers and other multiplexing devices to
combine additional pump sources.
10 Circulator 56 and grating 44, shown in Fig. 10, are
typically more expensive than coupler arrangements.
15 5 However, as the number of pump sources 32_a is increased, the
circulator/grating devices can reduce the loss associated
with pump combining. The circulators 56 can be provided
20 with a plurality of ports and corresponding gratings to
combine the pump wavelengths. One or more circulators 50
10 can also be cascaded to provide for more efficient
combining of the pump wavelengths.

20 The configuration shown in Fig. 3 was used to further
demonstrate the advantages of the present invention. In
one example, four pump wavelengths, 1450, 1460, 1485, and
25 1495 nm, were combined using two 10 nm DWDM couplers and a
dichroic filter, which allows the unevenly spaced
wavelengths to be effectively combined. The combined pump
wavelengths were supplied to DCF to provide Raman gain in
30 the transmission signal wavelength range of 1555 to 1585
20 nm.

30 As shown in Fig. 11(a), substantially flat Raman gain
signal variation profiles (± 0.16 dB) can be produced over
a 30 nm range for gains ranging from 1 to 8 dB. In
addition, the relative power of the pump wavelengths
35 25 supplied to the device 12 can be varied to produce non-
linear profiles that generally increase or decrease across
the signal wavelength range, as shown in Fig. 11(b).

40 Experimental gain profiles were determined for a
number of additional pump wavelengths. Based on the
30 experimental results, Raman signal varying device
simulations were performed over 35 nm wide (1530-1565 nm)
and 100 nm wide (1530-1630 nm) signal wavelength ranges.
45 The predicted performance of ± 0.12 dB and ± 0.342 dB over
the 35 nm and 100 nm wavelength ranges, as shown in Figs.
35 12 (curve a) and 13, respectively, indicates that the
signal varying devices of the present invention can be used
50 over a wide range of wavelengths to accommodate numerous

5 channels. Fig. 12 (curves b and c) also shows examples of
10 linear and non-linear profiles that can be produced by
varying the relative power at the various pump wavelengths.
15 It is also expected that the number of pumps and the pump
20 wavelength spacing can be further varied to provide a range
25 of signal variation profiles over wide and narrow
wavelength ranges.

30 The signal varying devices 12 of the present invention
35 can be operated in one, two, or three of the signal varying
40 modes, amplification, attenuation, and lossless. By
45 controlling the pump power, one signal varying device can
50 be continuously transitioned between the three modes of
55 operation. In addition, the intensity gain/loss profile
60 can be adjusted in each signal varying device 12 to
65 dynamically control the characteristics of the optical
70 signals exiting the signal varying device 12. It is also
75 possible to operate the signal varying device 12 in more
80 than one mode at the same time. For example, the signal
85 varying device 12 can be operated as an amplifier over part
90 of the signal wavelength range and as an attenuator and/or
95 a lossless link over the remaining part of the signal
wavelength range. The multiple mode operation of the
100 signal varying device 12 can be used to compensate for
105 optical signals that enter the signal varying device 12
110 with a non-linear intensity profile.

115 Different signal varying devices 12 can be included in
120 the system 10 that are operated with different pump
125 wavelengths and powers to provide a cumulative signal
130 variation profiles differing from the signal variation
135 profiles of each device 12. For example, the pump
140 wavelengths used in different devices 12 can be varied to
145 compensate for individual device signal variation profile
150 nonuniformities and provide a cumulative signal variation
155 profile that is substantially more uniform than the
160 individual device profiles.

165 Devices 12 of the present invention provide
170 flexibility in the control of the optical system 10,
175 because the power level, i.e. amplification and/or

5 attenuation level, can be varied without changing the
signal varying profile. Control of the individual devices
can be performed as is known in the art. Alternatively,
the devices 12 along the transmission fiber 28 can be
10 5 controlled as one or more groups to provide additional
stability in the system 10. An example of such an optical
control systems is disclosed in commonly assigned U.S.
Patent Application Serial No. 09/119,561, which is
15 incorporated herein by reference.

10 Unlike prior art systems, the present invention does
not require that a number of non-linear devices be
coordinated and controlled to provide linear intensity
20 variation (gain/loss) profiles. Instead, the present
invention provides an optical system incorporating a
25 15 continuous transition signal varying device that provides
increased control over the characteristics of optical
signals being transmitted in the system.

25 Those of ordinary skill in the art will appreciate
that numerous modifications and variations that can be made
30 20 to specific aspects of the present invention without
departing from the scope of the present invention. It is
intended that the foregoing specification and the following
claims cover such modifications and variations.

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Claims

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CLAIMS

What is claimed is:

1. An optical transmission system comprising:

a plurality of optical processing nodes configured to
10 optically communicate via optical signals in a signal
wavelength range; and,

15 a plurality of signal varying devices positioned to
vary an optical signal passing between said processing
nodes, wherein said plurality of signal varying devices

10 includes

20 a first signal varying device at a first location
including optical fiber provided with optical energy in a
first set of pump wavelengths from a first pump source to
produce Raman gain having a first signal variation profile
15 in the optical signals over the signal wavelength range,
and

25 a second signal varying device at a second location
remote from said first location and configured to provide a
second signal variation profile over the signal wavelength
20 range, wherein said first and second signal variation
profiles provide for a cumulative signal variation profile
30 over the signal wavelength range that differs from either
of the first and second signal variation profiles.

35 2. The system of claim 1 wherein said first pump

25 source is configured to vary at least one of the pump
energy carried by at least one of said pump wavelengths and
at least one of the pump wavelengths to control at least
40 the first signal variation profile.

30 3. The system of claim 1 wherein said first pump

35 source includes pump wavelengths selected to provide a
45 substantially uniform signal variation profile over the
signal wavelength range.

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5 4. The system of claim 1 wherein said second signal
varying device includes at least one doped optical fiber
configured to optically amplify the optical signals; and,
 said first pump source is further configured to supply
10 5 pump energy to optically amplify optical signals in said
 doped fiber.

15 5. The system in claim 4 wherein said first pump
source includes pump wavelengths selected to provide an
adjustable overall gain profile over the signal wavelength
10 range.

20 6. The system in claim 4 wherein said optical fiber
includes at least a portion of transmission fiber in said
optical transmission system.

25 7. The system in claim 4 wherein said first pump
15 source includes pump wavelengths selected to provide a
substantially uniform overall gain profile over the signal
wavelength range.

30 8. The system in claim 4 wherein said first pump
source includes pump wavelengths selected to provide
20 different Raman and doped fiber gain profiles over the at
least one signal wavelength range.

35 9. The system of claim 4 wherein said doped fiber
includes at least one erbium doped fiber.

40 10. The system of claim 9 wherein said first pump
25 source is configured to control the pump wavelength to
provide a Raman gain profile that substantially compensates
for gain non-uniformities introduced by said at least one
erbium doped fiber.

45 11. The system of claim 4 further comprising at least
30 one wavelength selective reflector positioned to reflect a
portion of the pump energy from at least one pump
wavelength back toward said first pump source.

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5 12. The system of claim 11 wherein said at least one wavelength selective reflectors includes at least one fiber Bragg grating positioned to reflect the portion of the at least one pump wavelength before reaching said doped fiber.

10 5 13. The system of claim 10 wherein said first pump source is configured to supply pump energy in at least one wavelength that is not absorbed by said doped fiber and to provide Raman gain in said optical fiber.

15 14. The system of claim 1 wherein said first pump source is remotely located from said optical fiber and delivers the pump energy to said optical fiber via a separate pump path.

20 15. The system of claim 1 wherein said optical fiber includes first and second Raman fiber, said first Raman fiber having different Raman gain characteristics than said second Raman fiber; and,

25 30 said first pump source is configured to provide pump energy in pump wavelengths to produce Raman gain in said first and second Raman fibers.

35 20 16. The system of claim 1 wherein said first Raman fiber includes optical fibers having a smaller core than said second Raman fiber.

40 35 17. The system of claim 16 wherein said first pump source is configured to provide a common source of pump energy to said first and second Raman fibers.

45 40 18. The system of claim 17 wherein said second Raman fiber provides for low loss in the 1420 to 1510 nm range and pump energy is transmitted through said second Raman fiber to said first Raman fiber.

50 45 30 19. The system of claim 16 wherein said first pump source is configured to provide different Raman pump wavelengths to said first Raman fiber and said second Raman fiber.

5 20. The system of claim 1 wherein said second signal
varying device includes a second pump source configured to
provide pump energy in at least a second set of Raman
wavelengths to provide Raman gain in the first set of Raman
10 5 wavelengths in said optical fiber.

15 21. The system of claim 20 wherein said second set of
Raman wavelengths is counter-propagated in said optical
fiber relative to the first set of Raman wavelengths.

20 22. The system of claim 20 wherein said first pump
10 source includes a third set of Raman wavelengths to provide
Raman gain to the second set of Raman wavelengths.

25 23. The system of claim 1 wherein a portion of said
optical fiber provides for distributed Raman gain and
another portion of said optical fiber provides for
15 concentrated Raman gain.

30 24. The system of claim 23 further comprising a gain
flattening filter positioned to impart a signal variation
profile over at least a portion of at least one signal
wavelength range.

35 20 25. The system of claim 1 wherein said pump
wavelengths are selected to provide a cumulative signal
variation profile over the signal wavelength range having a
variation of <±1 dB.

40 26. The system of claim 1 wherein said device is
25 operable in at least one signal varying mode, said mode
selected from the group consisting of amplification,
attenuation, and lossless transmission.

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5 27. The system of claim 1 wherein said optical fiber
is suitable for transmitting a plurality of signal
wavelength ranges; and,

10 said first pump source is configured to provide a
5 plurality of pump wavelength interleaved with the plurality
of signal wavelength ranges and having sufficient pump
energy to produce Raman gain in a plurality of signal
varying profiles in the plurality of signal wavelength
15 ranges.

20 10 28. The system of claim 1 wherein said optical fiber
is configured to produce Raman gain in a signal wavelength
range and provide concentrated amplification, attenuation,
25 and lossless transmission in said optical fiber; and,

25 said first pump source is configured to provide pump
15 energy to said optical fiber in a plurality of pump
wavelengths having sufficient pump energy to produce Raman
gain and a signal variation profile in the signal
wavelength range and said pump source is further configured
30 to control the pump energy in at least one of said pump
20 wavelengths to vary the signal variation profile and
provide amplification, attenuation, and lossless
transmission in said optical fiber over the signal
wavelength range.

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5 29. A method of controlling signal variation of
optical signals in an optical transmission system
comprising:

10 providing a first signal varying device including an
optical fiber provide with pump energy in a plurality of
pump wavelengths from a first pump source and configured to
produce Raman gain having a first signal variation profile
in optical signals over the signal wavelength range;

15 providing a second signal varying device at a second
location remote from said first location and configured to
provide a second signal variation profile over the signal
wavelength range, wherein said first and second signal
variation profiles provide for a cumulative signal
variation profile over the signal wavelength range that
20 differs from either of the first and second signal
variation profiles; and,

25 controlling the pump energy produced by at least one
of said pump wavelengths to vary at least the first signal
variation profile over the signal wavelength range.

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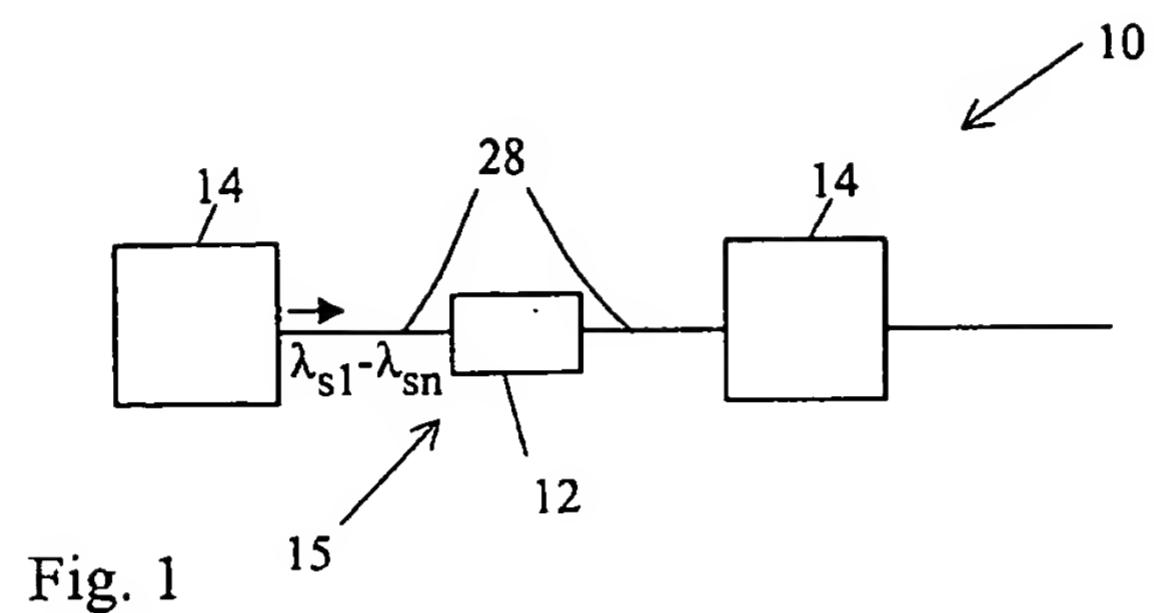


Fig. 1

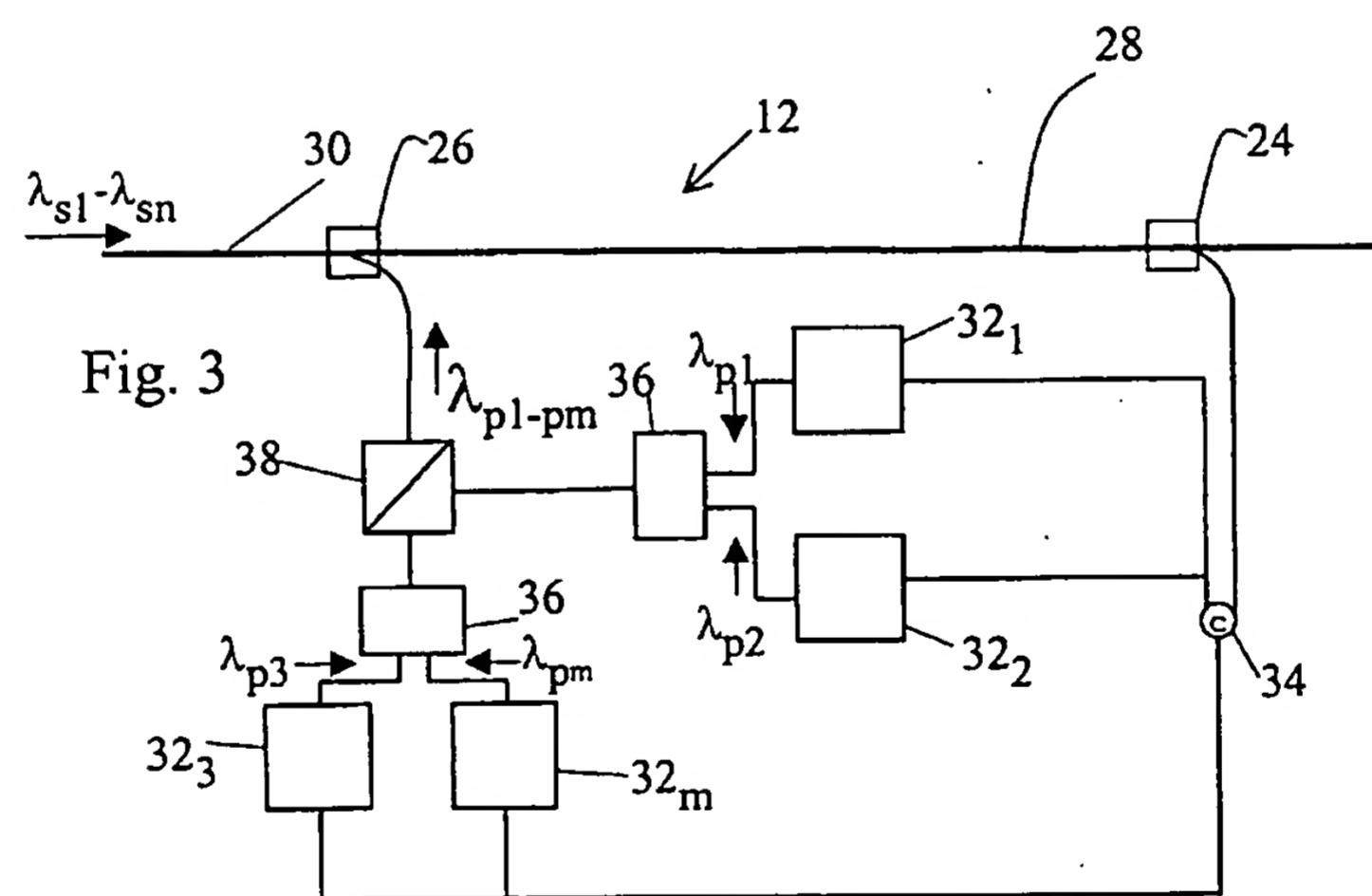


Fig. 3

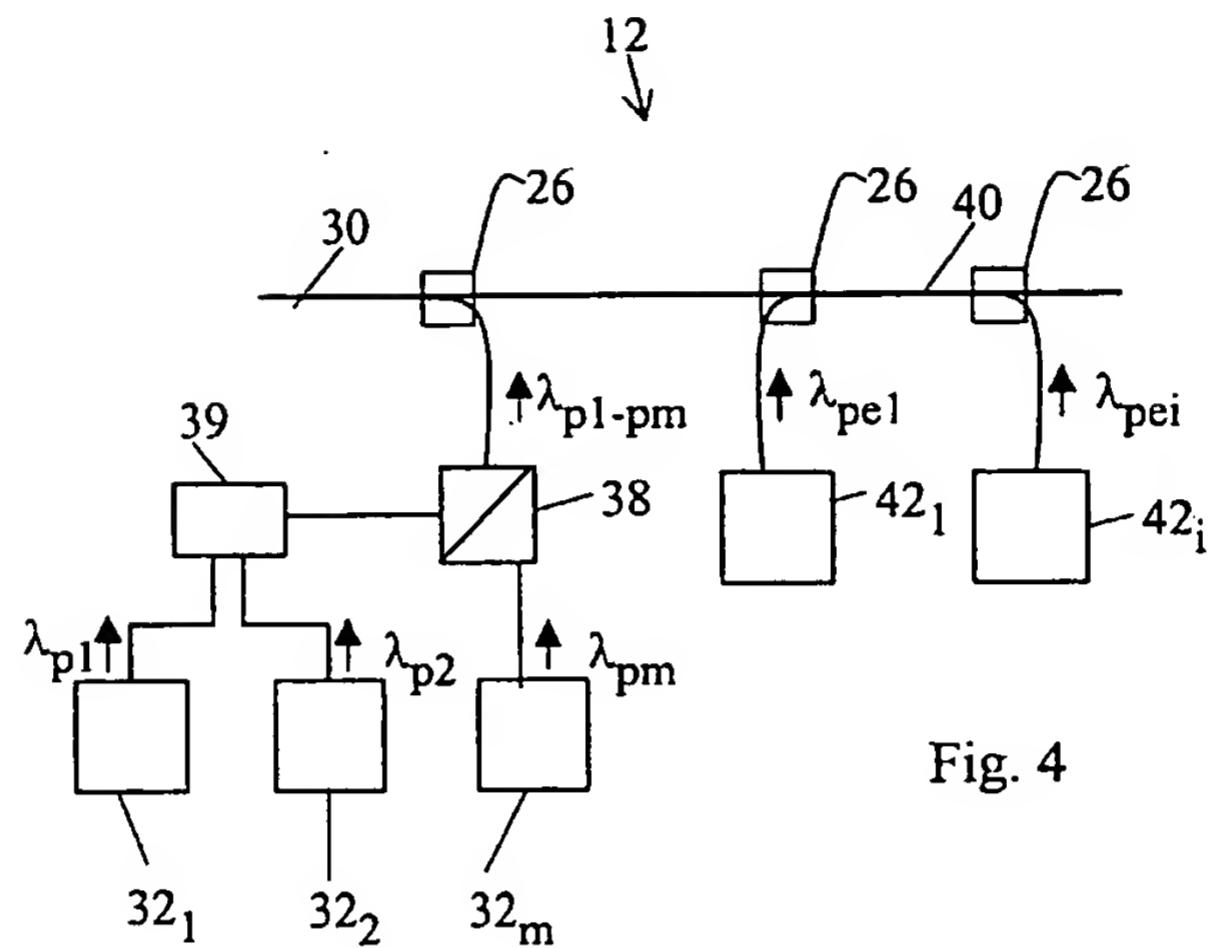


Fig. 4

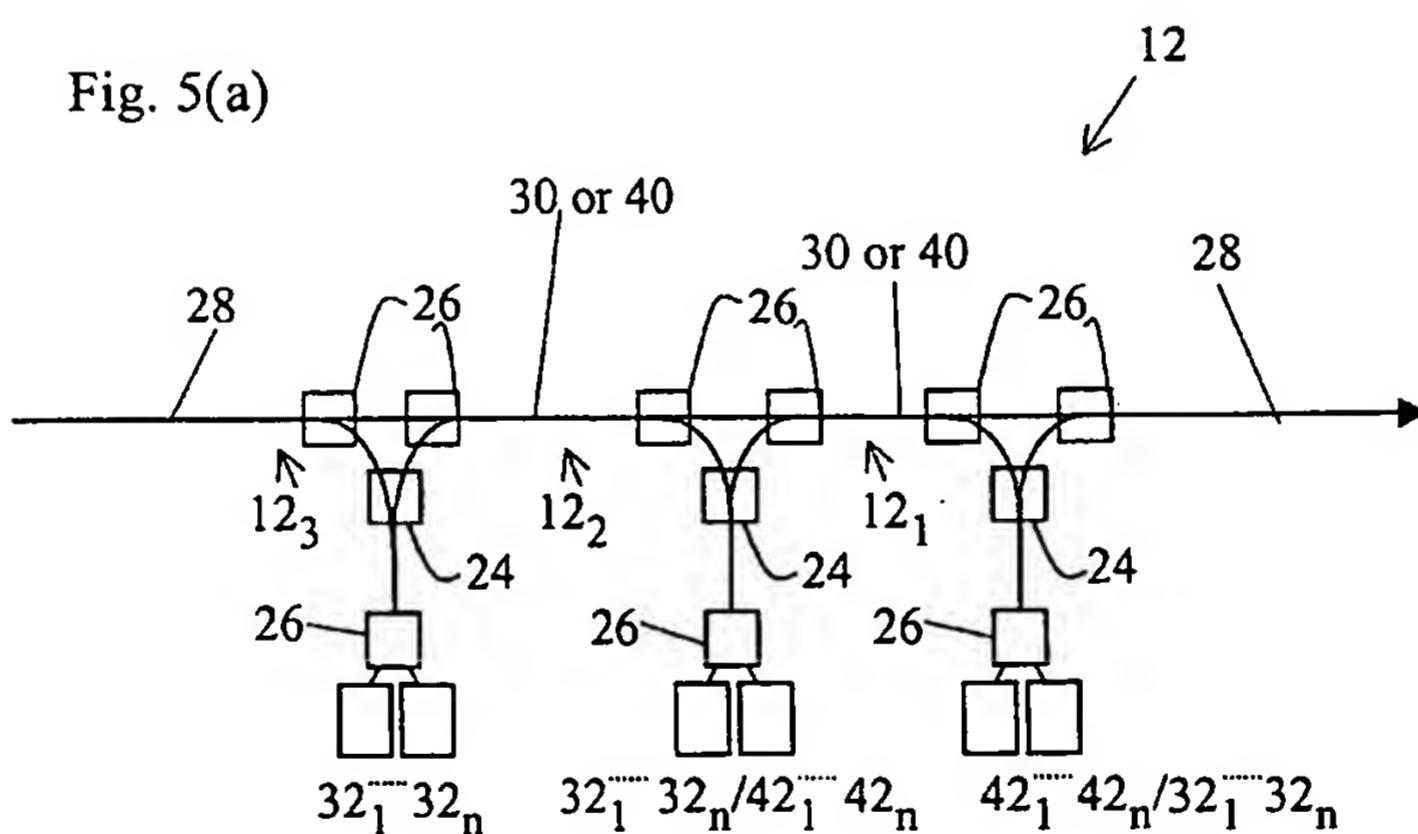
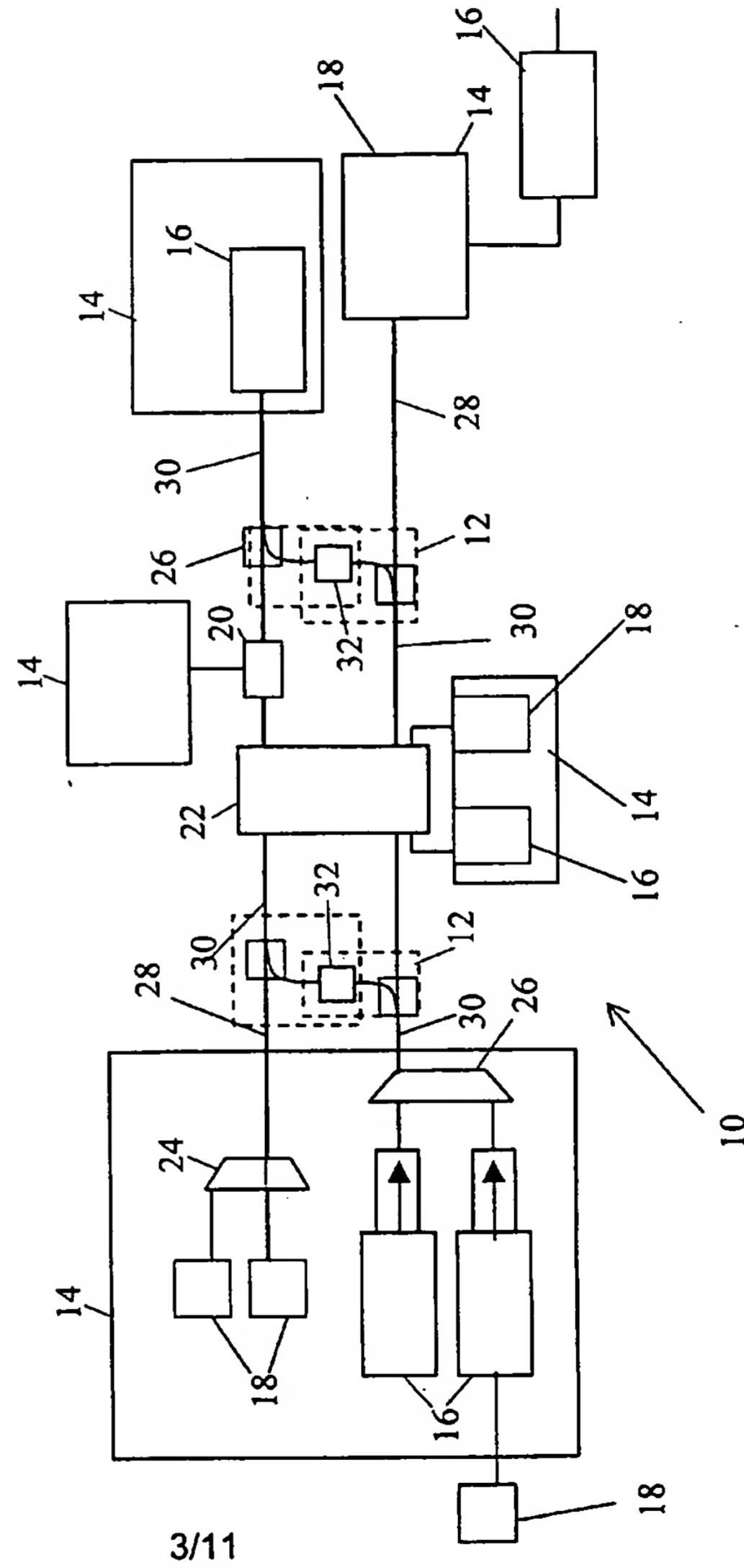


Fig. 2



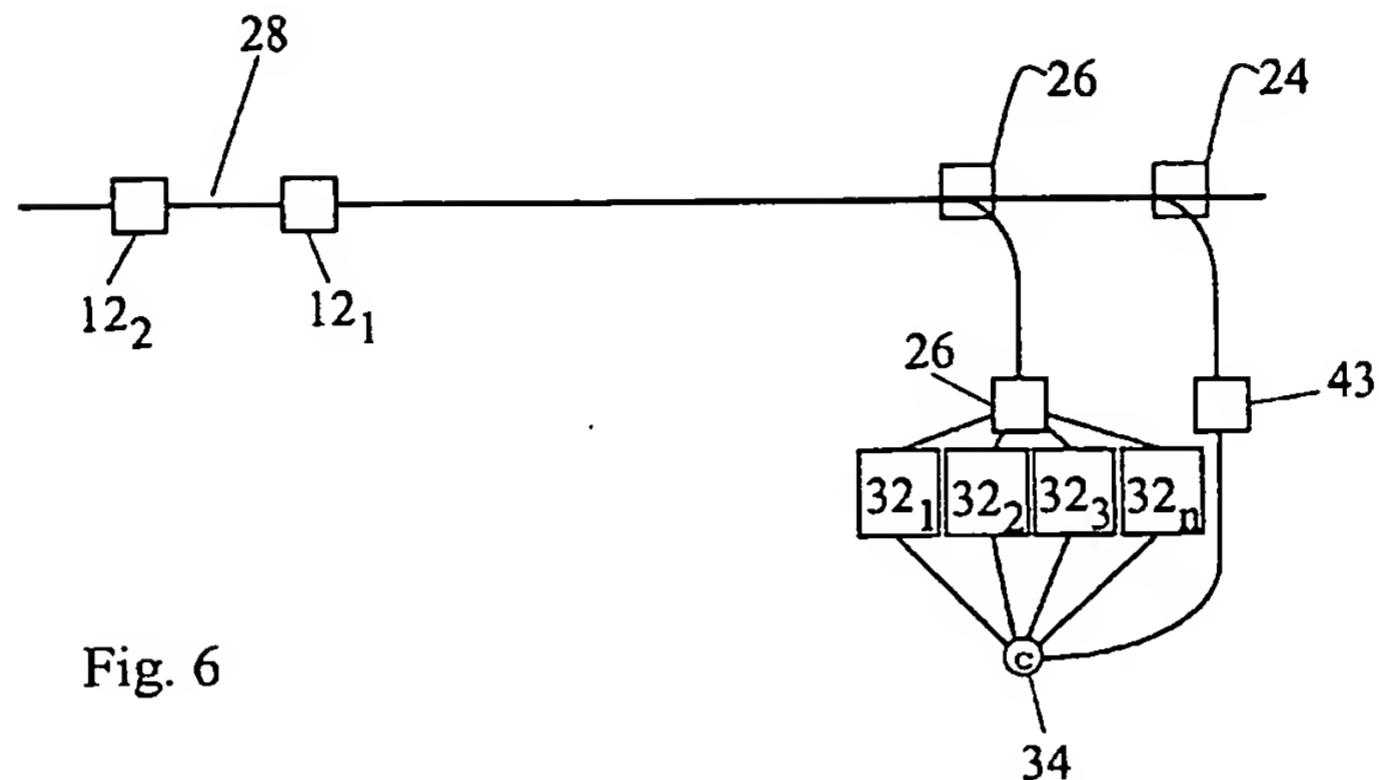


Fig. 6

Fig. 7

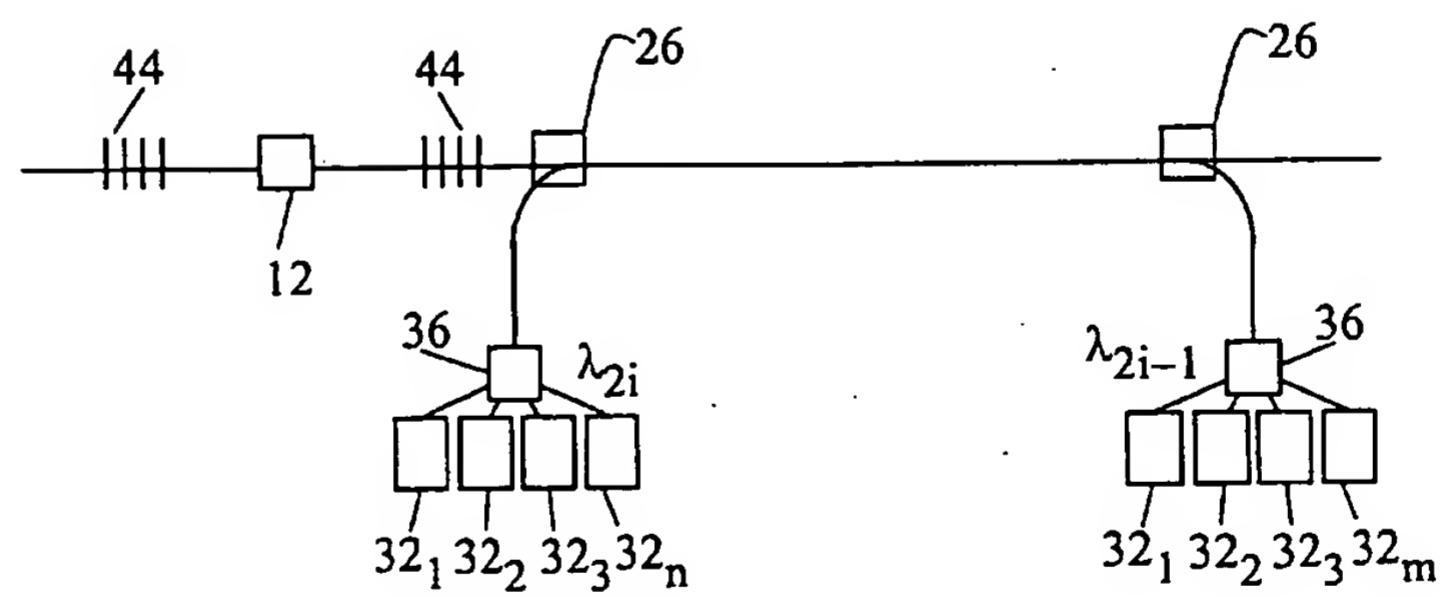


Fig. 9(a)

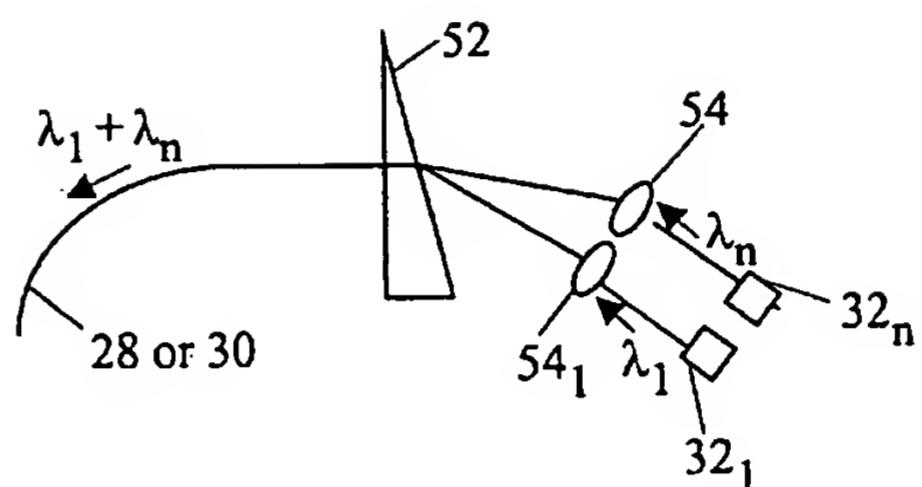


Fig. 9(b)

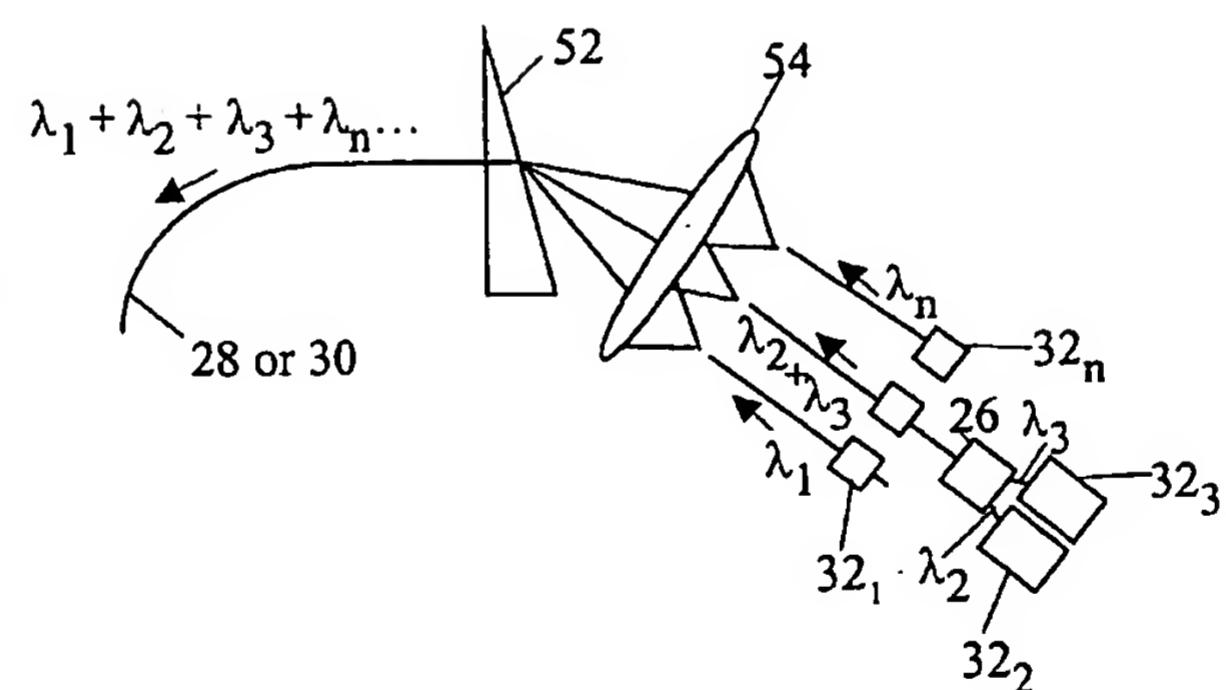


Fig. 8

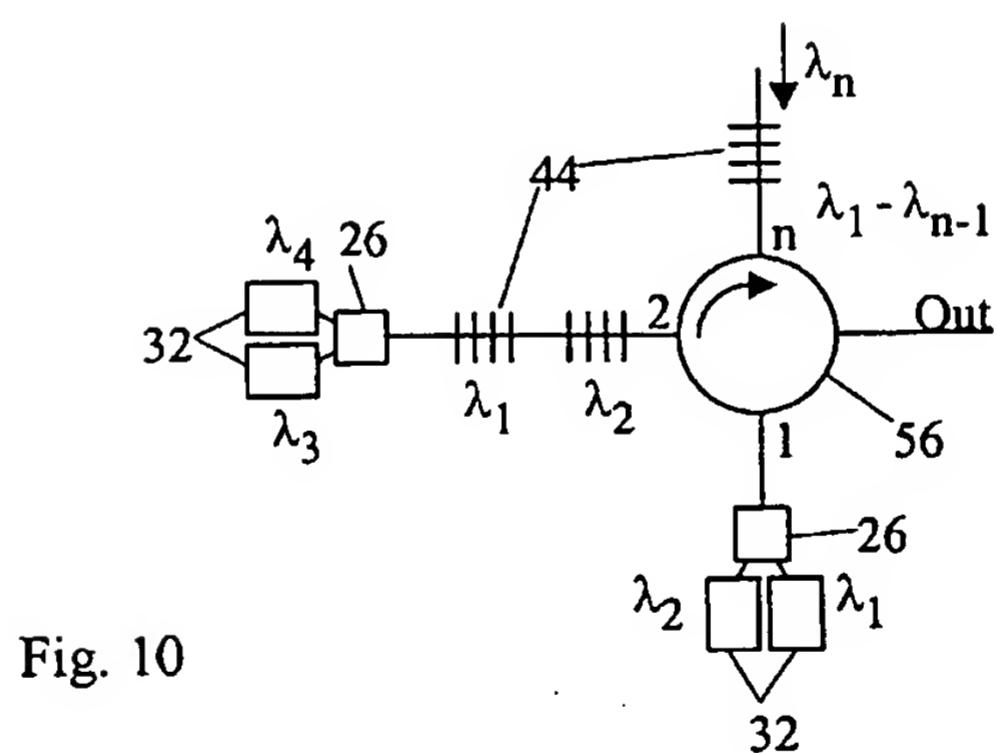
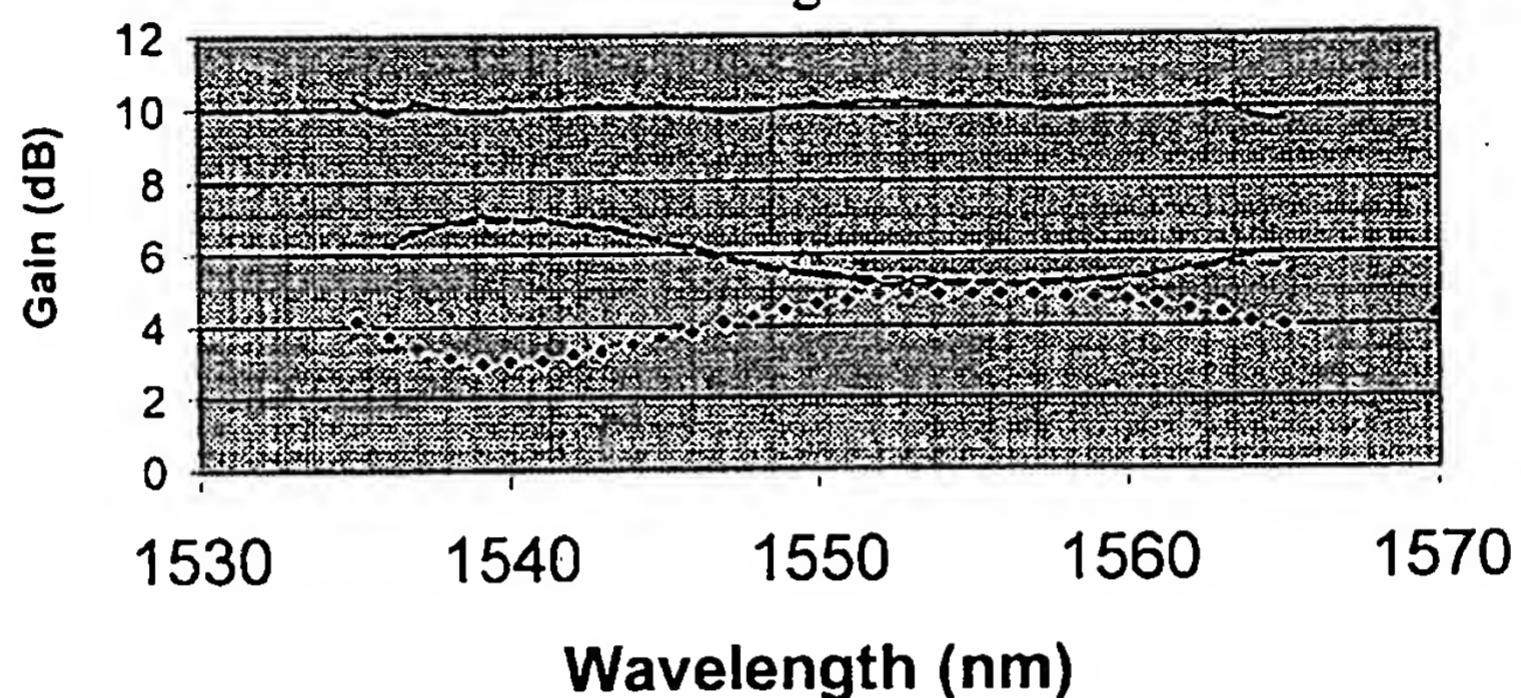


Fig. 10

Fig. 5(b)

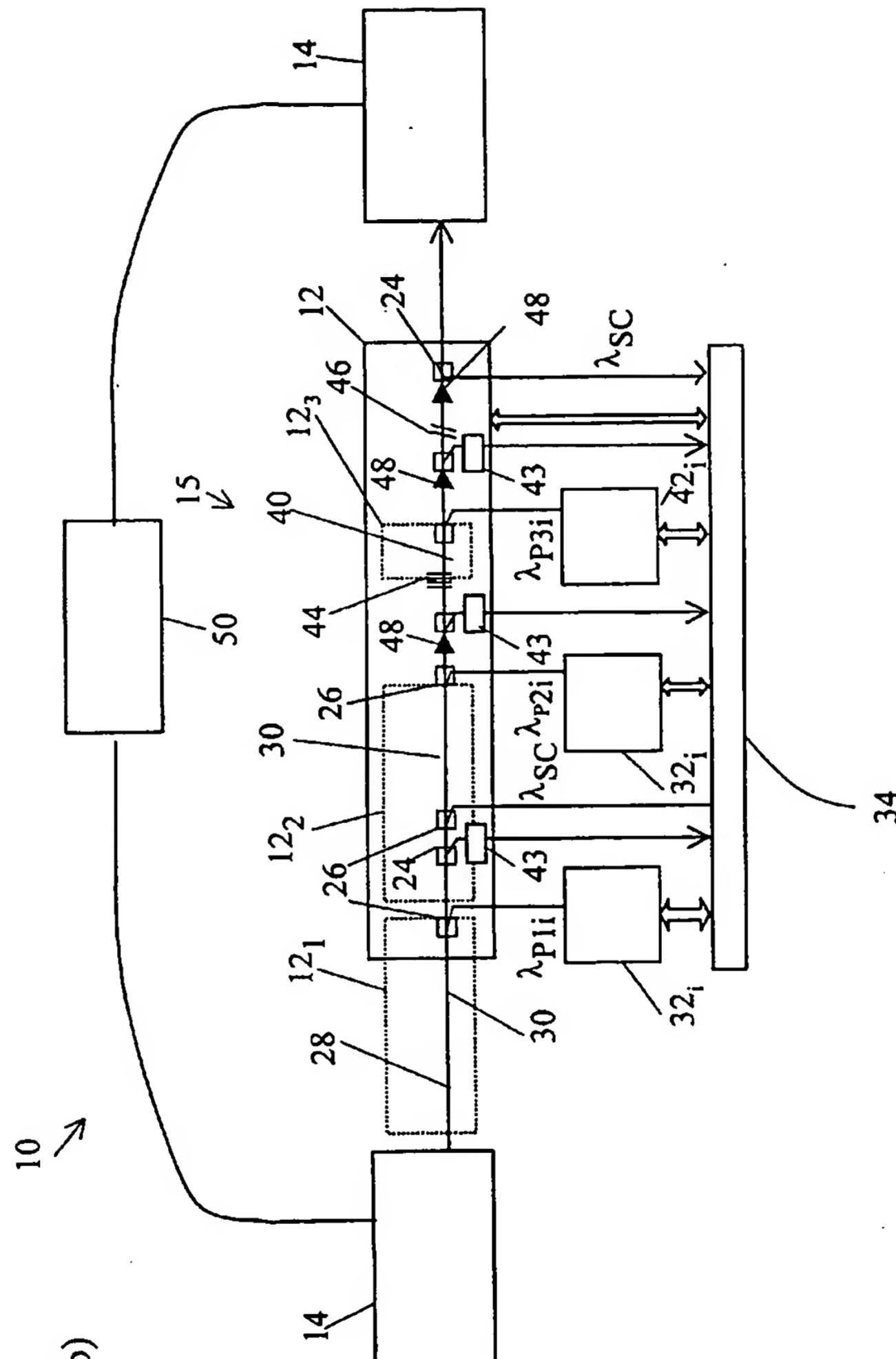


Fig. 11(a)

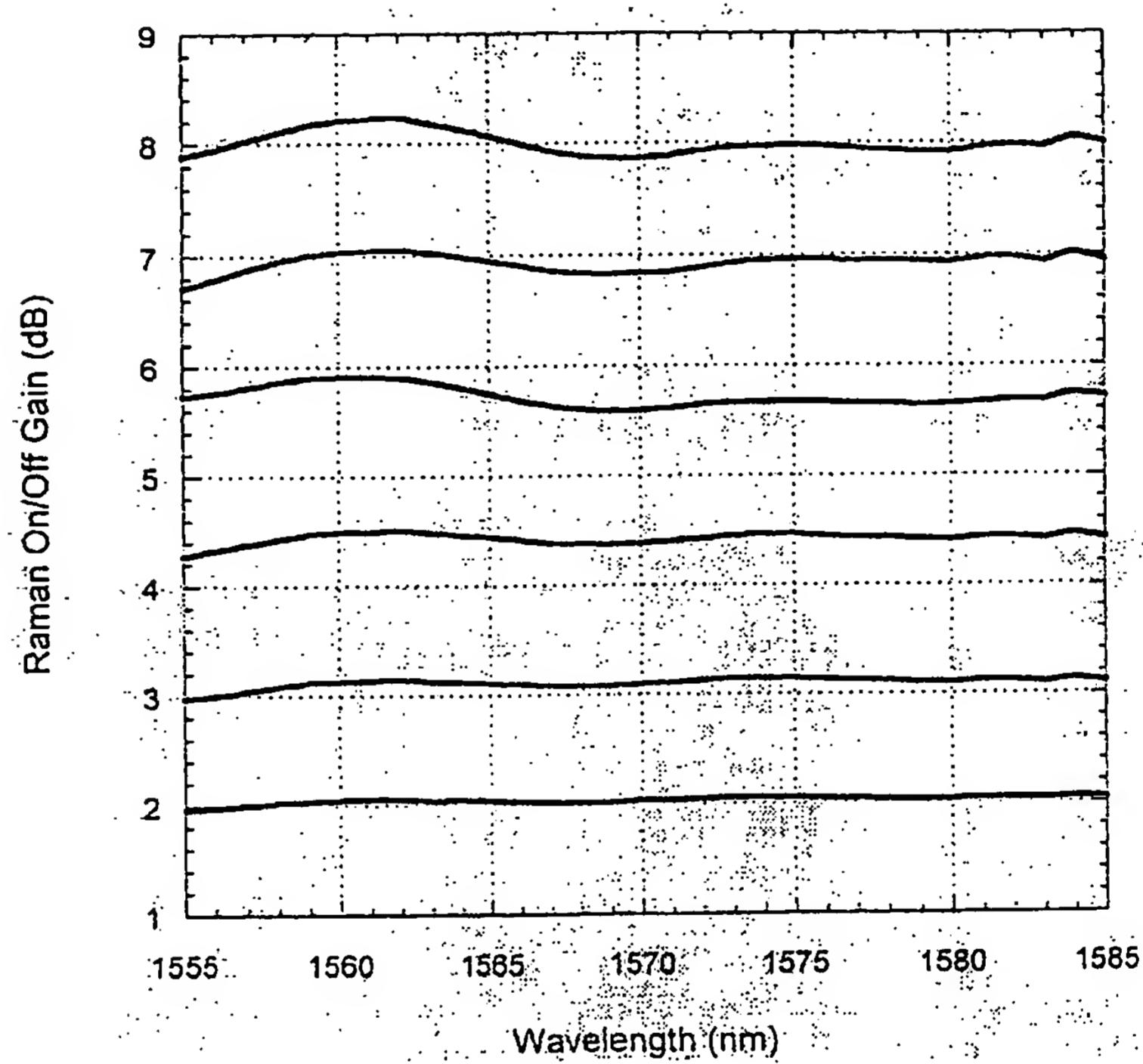


Fig. 11(b)

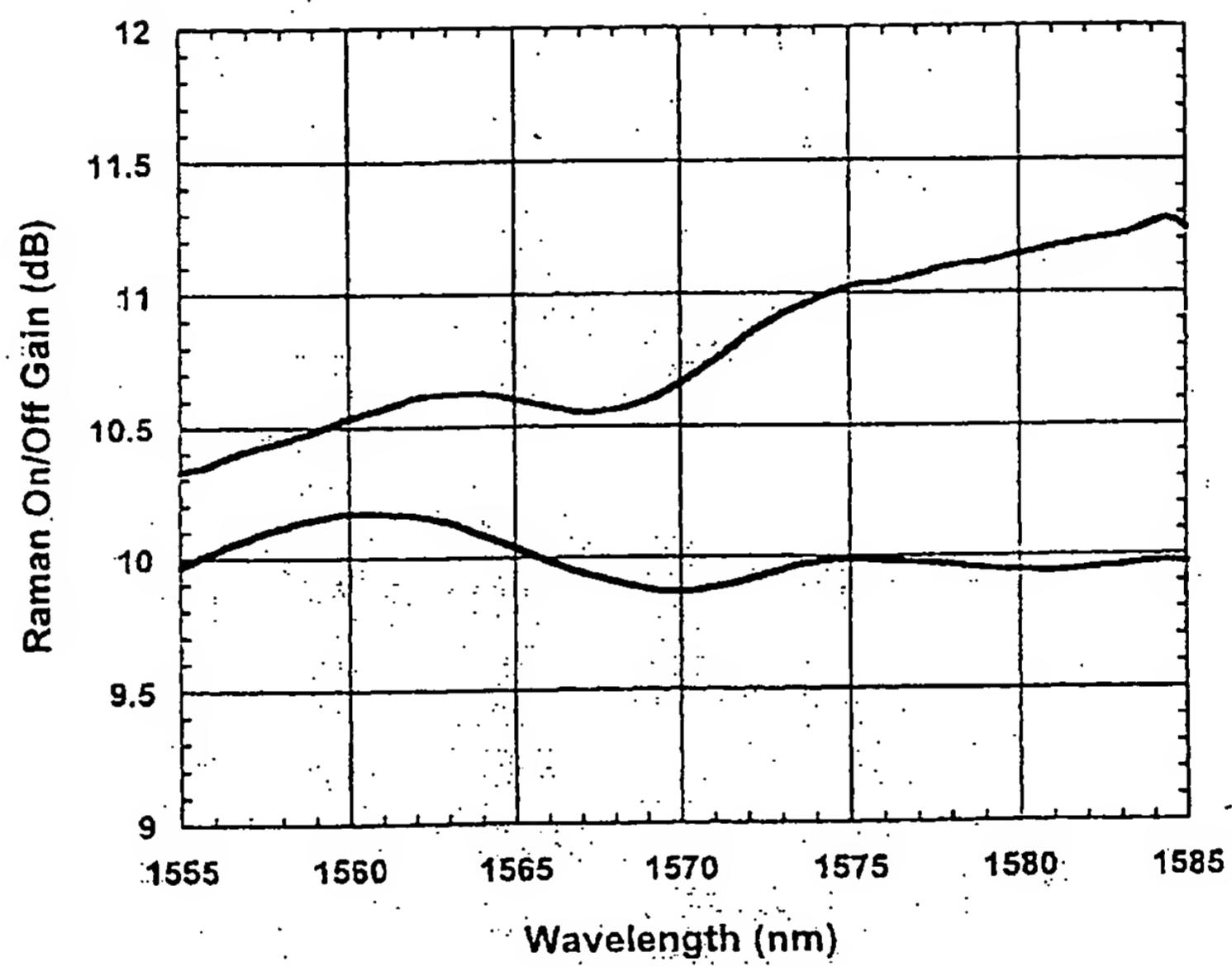


Fig. 12

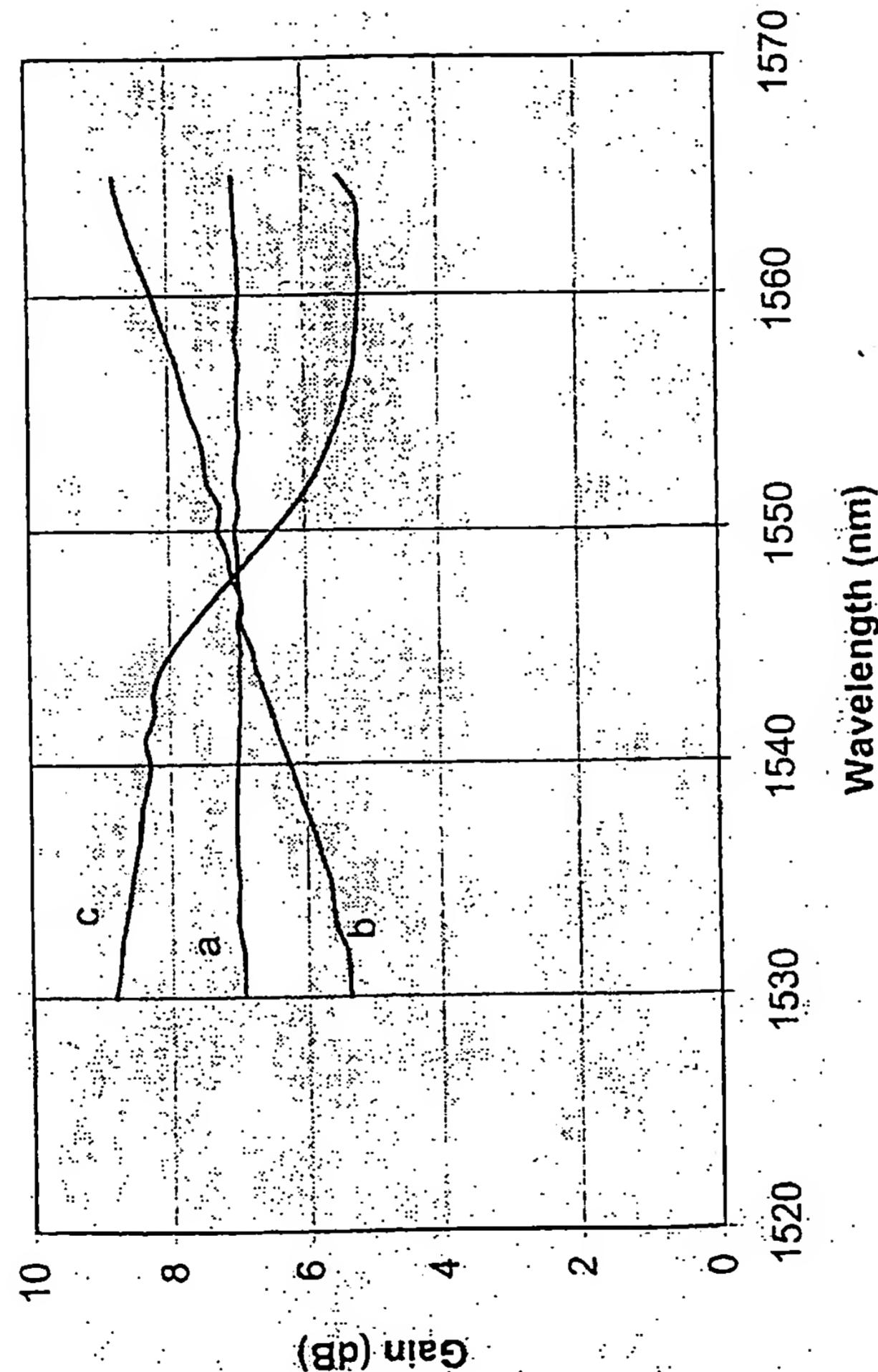


Fig. 13

